

<b>REPORT DOCUMENTATION PAGE</b>			Form Approved OMB NO. 0704-0188	
Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE April 2004		3. REPORT TYPE AND DATES COVERED Final Report; 7/24/2000 – 1/23/2004.
4. TITLE AND SUBTITLE Simultaneous Vibration Isolation and Damping Control via High Authority Smart Structures		5. FUNDING NUMBERS <del>DAAD19-00-1-0462</del>		
6. AUTHOR(S) Kon-Well Wang				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dr. Kon-Well Wang 157E Hammond Building The Pennsylvania State University University Park, PA 16802		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSORING / MONITORING AGENCY REPORT NUMBER <del>DAAD19-00-1-0462</del> 40281-EG • 3		
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by the documentation.				
12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12 b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) The goal of this proposed research is to investigate a new class of high authority smart structures to <i>isolate</i> vibration (isolate main structure from disturbance source) and <i>control</i> vibration (of the sub-structure with disturbance source) <i>simultaneously</i> in a multi-mode environment. The idea is to develop novel multi-loop piezoelectric networks and control schemes for multi-frequency, and varying-frequency disturbance absorptions and isolations. During this research period, the PI and his students have achieved the following: (a) Developed active-passive piezoelectric network systems and controller for vibration isolation/absorption of excitations with varying frequency; (b) Developed a multi-loop active-passive piezoelectric network isolator/absorber for multiple varying frequency disturbance rejections; (c) Performed single actuator experimental investigation and parametric study; and (d) Explored multiple actuator systems on complex structures. The analytical and experimental results have demonstrated that the proposed systems can outperform the current approaches and effectively achieve significant vibration absorption and isolation.				
14. SUBJECT TERMS piezoelectric absorbers and isolators, active-passive hybrid vibration controls, adaptive structures, piezoelectric materials, piezoelectric shunt			15. NUMBER OF PAGES 11 (including this one)	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)

Enclosure 1

# **SIMULTANEOUS VIBRATION ISOLATION AND DAMPING CONTROL VIA HIGH AUTHORITY SMART STRUCTURES**

**K. W. Wang**  
**Proposal No. 40281-EG**  
**Grant No. DAAD19-00-1-0462**

## **TABLE OF CONTENTS**

	<i>Page Number</i>
Table of Contents	1
List of Illustrations	2
Statement of the Problem Studied	3
Summary of the Most Important Results	3
List of Publications	10
Referred Journal Publication	10
Conference/Workshop Publications and Presentations	10
Participants	10
Report of Inventions	10

## LIST OF ILLUSTRATIONS

Figure 1. Schematic of a smart isolation pad with active-passive vibration piezoelectric absorber design. (Page 7)

Figure 2. Multiple-loop active-passive network for multi-frequency disturbance rejection. (Page 7)

Figure 3. Piezoelectric stack actuator vibration absorption/isolation experimental setup. (Page 8)

Figure 4. Experimental results - vibration amplitude (accelerometer signals) envelope under a harmonic disturbance with time varying frequency (excitation frequency ramping up). The active-passive network absorber can outperform an optimal passive system significantly. (Page 8)

Figure 5. Scaled helicopter tailboom structure with built-in piezoelectric actuators. (Page 9)

Figure 6. Analytical results of multiple actuators on tailboom structure: vibration amplitude (acceleration) envelope under a harmonic disturbance with time varying frequency (control initiated at time=2.25s, excitation frequency ramping up). (Page 9)

## STATEMENT OF THE PROBLEM STUDIED

The objective of this project is to investigate a new class of high authority smart structures to *isolate* vibration (isolate main structure from disturbance source) and *control* vibration (of the sub-structure with disturbance source) *simultaneously* in a multi-mode environment. The idea is to develop novel piezoelectric networks and control schemes for variable-frequency disturbance absorptions and isolations. Analytical and experimental efforts are pursued starting from a single actuator – single frequency excitation scenario, and expanded to multiple excitation frequency situations and multiple actuator configurations. This research investigates some fundamental and critical issues that have not been addressed in current active control or smart structure studies. These include: (1) create innovative piezoelectric network-based concepts and design schemes for multi-mode, multi-frequency, adaptable operations; and (2) develop control methodology to utilize the high authority characteristics of piezoelectric material-based actuators and the combined effect of both of their active and passive actions.

## SUMMARY OF THE MOST IMPORTANT RESULTS

### **(1) Active-Passive Piezoelectric Network Controller for Vibration Isolation/Absorption of Excitations with Varying Frequency**

It has been shown that piezoelectric materials can be used as passive vibration absorbers when shunted by electrical networks. Semi-active piezoelectric absorbers have also been proposed for suppressing harmonic excitations with varying frequency. While these absorber concepts can be useful for developing narrow band vibration isolators, such passive and semi-active devices have limitations that restrict their applications. The new concept explored here is a high performance active-passive alternative that uses a combination of a passive electrical circuit and active control actions (Figure 1). The active control consists of three parts: an *adaptive inductor tuning action*, a *negative resistance action*, and a *coupling enhancement action*. The active inductance is used to tune the piezoelectric absorber to track the disturbance frequency online via feedback control.

The performance and robustness of the absorber are further enhanced by using an active negative resistance to reduce the network inherent resistance (increase absorber vibration

suppression/isolation performance by increasing its frequency domain narrow band “notch”) and an active coupling feedback to enhance the electromechanical coupling. An optimal tuning law for a multiple-degrees-of-freedom system is derived using a quasi-steady-state approach. Conditions under which the stability of the closed-loop system can be guaranteed are also derived. It is shown through parametric studies that the proposed design can greatly outperform two state-of-the-art control methods (Filtered-X and APPN) for vibration suppression, while requiring less control effort.

## **(2) A Multi-Loop Active-Passive Piezoelectric Network Isolator/Absorber for Multiple Frequency Disturbance Rejections**

Since disturbance sources with multiple varying frequencies do occur in many real world applications, the objective of this sub-task is to expand the active-passive absorber/isolator concept to address the *multiple frequency* issue. In this research, a new multi-frequency adaptive piezoelectric vibration absorber/isolator design is presented. It uses *multiple-loop* networks consist of passive shunt circuits along with adaptive active control laws, as shown in Figure 2. The active control law enhances the passive piezoelectric absorber in four ways: it adds an adaptive tuning ability by imitating a variable inductance, it reduces the effective resistance in the absorber circuit to increase performance, it increases the effective coupling of the system to increase robustness and performance, and it effectively *decouples* the dynamics of the individual circuit branches. This decoupling action allows the tuning of the multi-frequency absorber to be calculated using an analytical optimal tuning law. The stability criteria of the multi-frequency piezoelectric absorber device are also derived.

The proposed design is shown to be effective for simultaneously suppressing two harmonic excitations with time-varying frequencies. For the purpose of comparison, the adaptive feedforward Filtered-X algorithm is used as a baseline. It is shown that the multi-frequency adaptive piezoelectric absorber can achieve better performance while requiring less control power, compared to the Filtered-X algorithm. The design and analysis presented here can also be extended in a straightforward manner to cases with three or more excitation frequencies.

### **(3) Single Actuator Experimental Investigation and Parametric Study**

Several conceptual designs of novel smart absorption/isolation devices have been explored. One is to utilize piezoelectric bimorph actuators and the other is to use piezoelectric stack actuators. Experimental investigations on a single piezoelectric stack actuator test stand are conducted for both off-resonant and near-resonant excitations. The test stand is an active-passive mount incorporating a piezoelectric stack actuator (Figure 3). Both vibration control and isolation actions are explored to demonstrate the versatility of the adaptive active-passive absorber. An inertial shaker is used to provide external disturbance. At the bottom of the test stand is a large spring-mass system simulating foundation dynamics. The active-passive mount, which is contained by two aluminum plates, is sandwiched between the vibrating source and the foundation. Between the plates is a piezoelectric stack actuator and four nylon struts, which are used to support the plate under moment and shear loads. The entire test stand is mounted on an optical isolation table. Since the frequency of the disturbance force is time varying, a frequency-tracking algorithm is included in the controller. It is shown that the vibration control performance of the proposed active-passive system is quite significant compared to the optimal passive baseline systems, even when the excitation frequency is changing rapidly (Figure 4) – an over 80% vibration reduction can be achieved under various spin up rates.

### **(4) Multiple Actuator Systems on Complex Structures**

In the above sub-tasks, only a single actuator is considered. In real world situations, normally *multiple-actuator* systems have to be used to effectively suppress vibration of complex structures. In this sub-task, the single adaptive absorber/isolator concept is expanded and developed for structures equipped with multiple actuators and circuits. The testbed structure used is a scaled helicopter tailboom with four built-in piezoelectric actuators (Figure 5). Both analytical and experimental investigations are being pursued. A new optimal tuning algorithm is developed for the adaptive inductor tuning action. This algorithm accounts for manufacturing differences and the placement of multiple actuators. Distributed accelerometers and a modal filter are employed to obtain the modal coordinates required for the active coupling feedback. This approach provides a viable alternative to a collocated displacement sensor for each actuator.

The structure is excited with a time varying frequency disturbance simulating a spin-up through a resonant frequency. With such a treatment, the analysis shows a 75% decrease in peak vibration as well as substantial broadband vibration reduction over the optimal passive baseline (Figure 6).

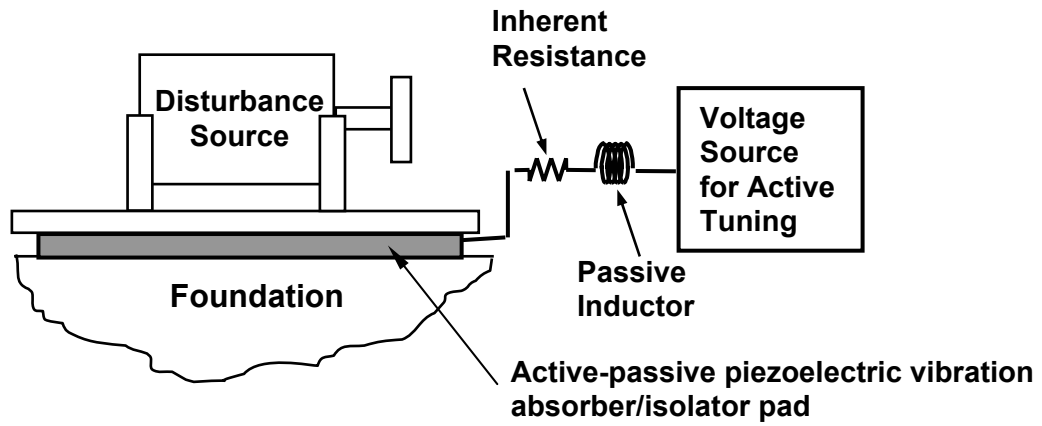


Figure 1. Schematic of a smart isolation pad with active-passive vibration piezoelectric absorber design

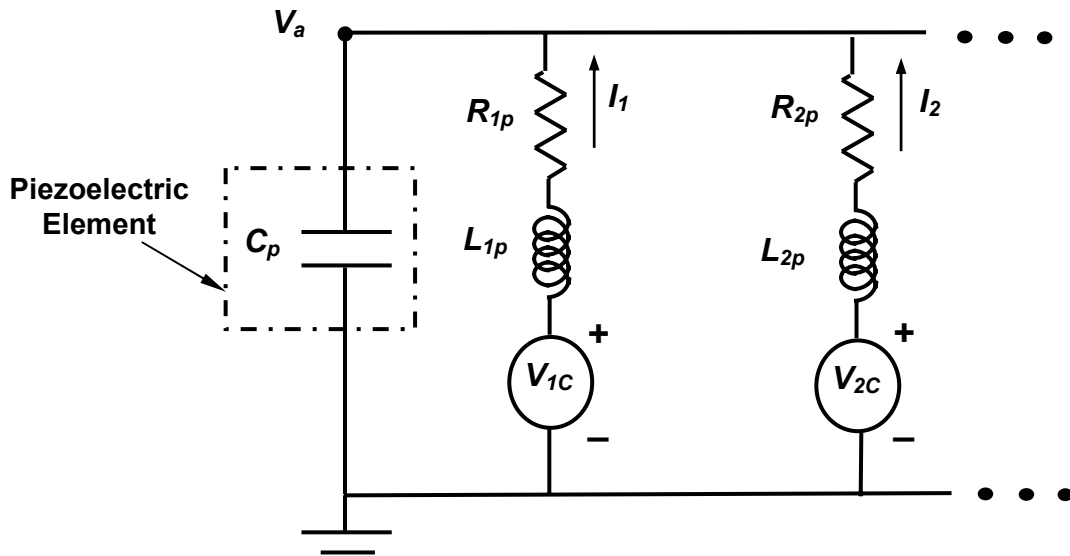


Figure 2. Multiple-loop active-passive network for multi-frequency disturbance rejection



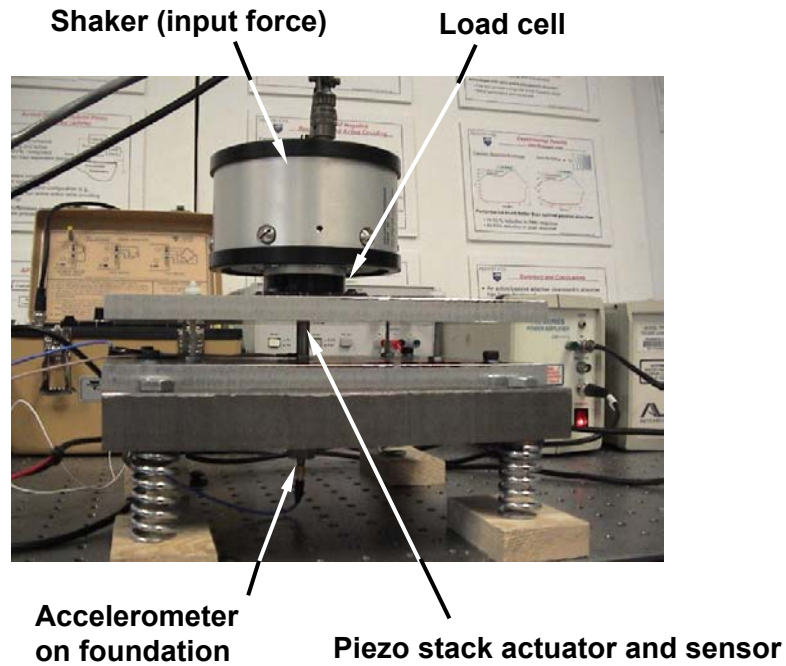


Figure 3. Piezoelectric stack actuator vibration absorption/isolation experimental setup

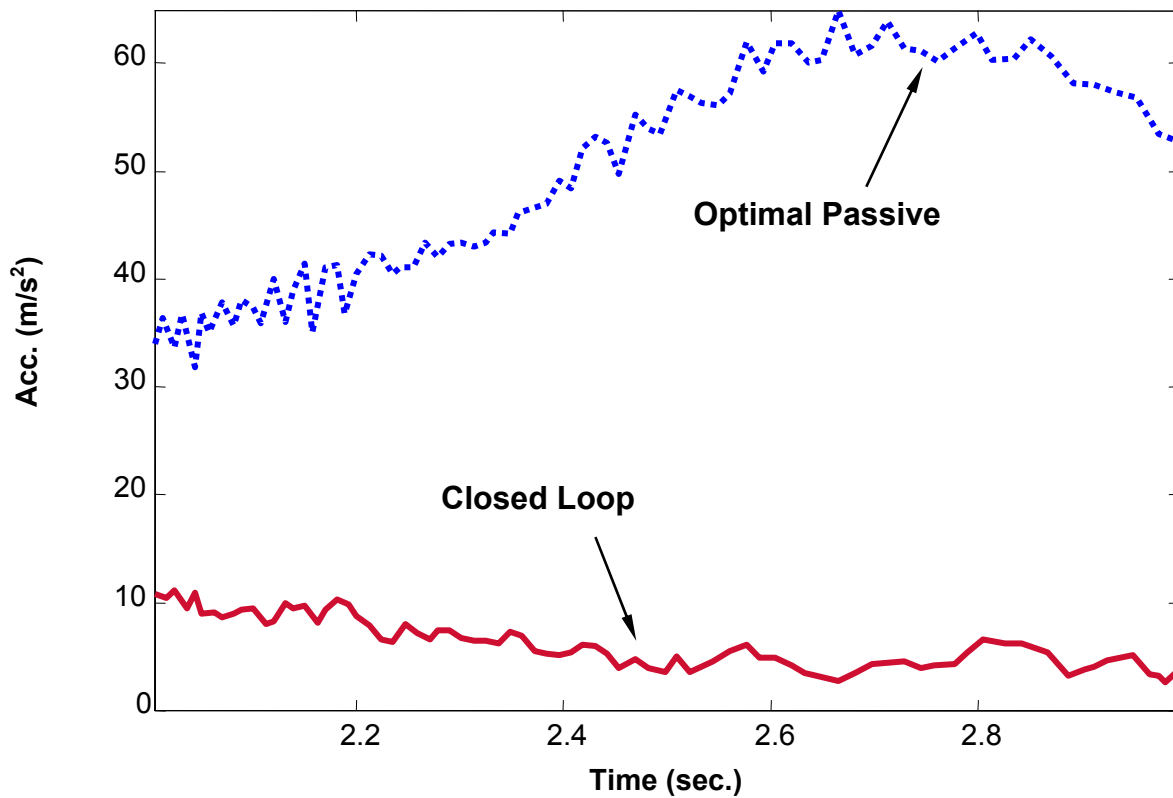


Figure 4. Experimental results - vibration amplitude (accelerometer signals) envelope under a harmonic disturbance with time varying frequency (excitation frequency ramping up). The active-passive network absorber can outperform an optimal passive system significantly.



Figure 5. Scaled helicopter tailboom structure with built-in piezoelectric actuators

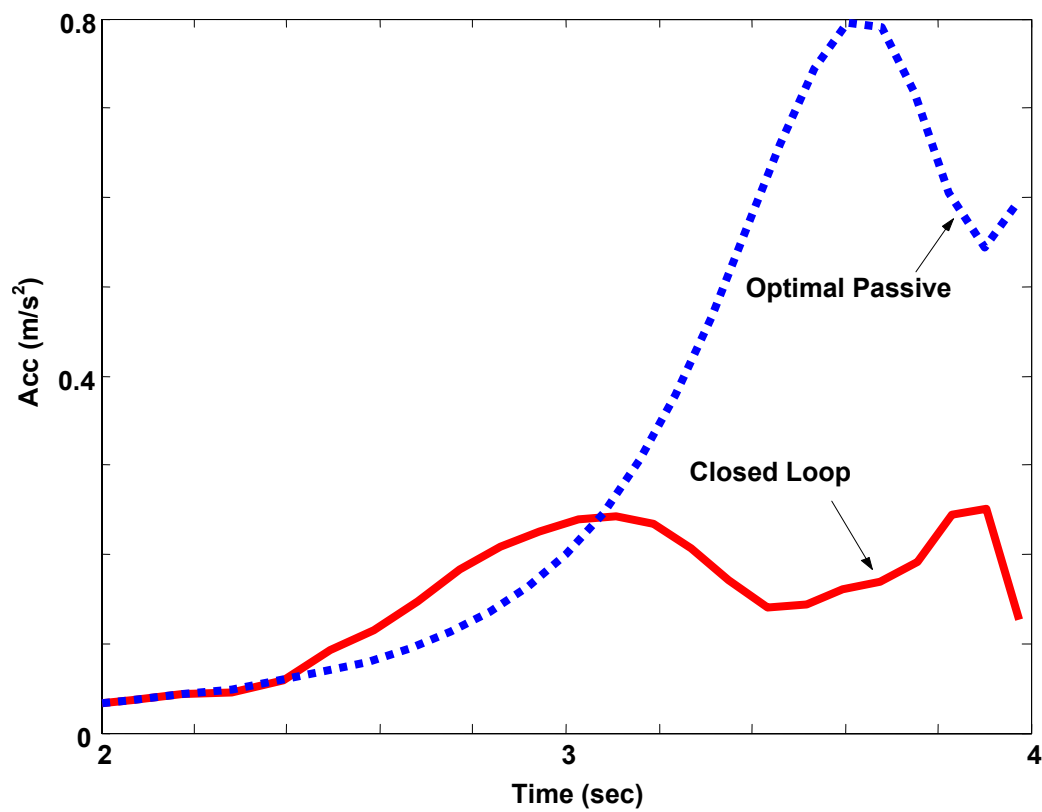


Figure 6. Analytical results of multiple actuators on tailboom structure: vibration amplitude (acceleration) envelope under a harmonic disturbance with time varying frequency (control initiated at time=2.25s, excitation frequency ramping up).

## LIST OF PUBLICATIONS

### Referred Journal Publication

R. Morgan and K. W. Wang, "An Active-Passive Piezoelectric Vibration Absorber for Structural Control under Harmonic Excitations with Time-Varying Frequency, Part 1: Algorithm Development and Analysis," *ASME Journal of Vibration and Acoustics*, 124(1), pp. 77-83, 2002.

R. Morgan and K. W. Wang, "An Active-Passive Piezoelectric Vibration Absorber for Structural Control under Harmonic Excitations with Time-Varying Frequency, Part 2: Experimental Validation and Parametric Study," *ASME Journal of Vibration and Acoustics*, 124(1), pp. 84-89, 2002.

R. Morgan and K. W. Wang, "Active-Passive Piezoelectric Absorbers for Suppression of Multiple Non-Stationary Harmonic Excitations," *Journal of Sound and Vibration*, 255(4), pp. 685-700, 2002.

### Conference/Workshop Publications and Presentations

R. Morgan, K. W. Wang, and J. Tang, "Active Tuning and Coupling Enhancement of Piezoelectric Vibration Absorbers for Variable-Frequency Harmonic Excitations in Multiple Degrees of Freedom Mechanical Systems," *Proc. SPIE Conf. on Smart Structures and Materials*, vol. 3985, pp. 497-509, 2000.

R. Morgan, K. W. Wang, "An Active-Passive Piezoelectric Vibration Absorber For Structural Control Under Harmonic Excitations With Time-Varying Frequency," *Proc. ASME IMECE*, AD-60, pp. 285-298, 2000.

R. Morgan and K. W. Wang, "A Multi-frequency Piezoelectric Vibration Absorber for Variable Frequency Harmonic Excitations," *Proc. SPIE Conf. on Smart Structures and Materials*, vol. 4331, pp. 130-140, 2001.

R. Morgan and K. W. Wang, "An Adaptable Active-Passive Piezoelectric Absorber For Nonstationary Disturbance Rejection -- Theory and Implementation," *Proc. of International Conference on Adaptive Structure Technology*, College Park, MD, 2001.

D. Belasco and K. W. Wang, "Structurally Integrated Piezoelectric Stack Absorbers for Nonstationary Disturbance Rejection," *Proc. Fifth International Conference on Intelligent Materials*, State College, PA, 2003.

## PARTICIPANTS

Personnel supported: K. W. Wang (PI), Ronald Morgan (graduate student) and David Belasco (graduate student).

## REPORT OF INVENTIONS

None.